Foot-and-Mouth Disease:

Sources of Outbreaks and Hazard Categorization of Modes of Virus Transmission

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Contents

EXECUTIVE SUMMARY

Foot-and-mouth disease (FMD), a highly contagious viral disease affecting primarily cloven-hoofed animals, continues to be a concern in the United States even though the last outbreak in North America was eradicated in 1954. Increased trade, decreased transit time of animals and animal products, and changes in sanitary standards provide opportunity for FMD reintroduction into the United States. An unchecked FMD outbreak could cost billions of dollars. Because the last U.S. outbreak of FMD was in 1929, most producers and animal health workers are inexperienced with the disease.

This document is a first step in formulating a strategic approach to evaluate FMD risk for North America, especially the United States. A brief description of FMD epidemiology is given, followed by a summary of the locations of past primary FMD outbreaks throughout the world by source. A qualitative approach is used to rank the possible modes of foot-and-mouth disease virus (FMDV) transmission by relative biologic hazard only.

The purpose of the hazard categorization is to better understand the relative importance of FMDV sources and to serve as a starting point for assessing the risk of FMD for North America. Other factors necessary for a complete FMD risk assessment, such as region of origin, destination, and quarantine methods, were not considered.

Three general assumptions were made: (1) live animals are exposed to FMDV; (2) products are derived from FMDV-infected animals; and (3) fomites or other vehicles come in contact with FMDV. Separate hazard categories exist for live animals and for animal products and fomites or other vehicles because different criteria were used to determine the categories for each. The criteria that were used to rank live animals were: (1) whether the animal is a natural or experimental host; (2) whether the animal has transmitted FMDV to other animals; and (3) length of carrier status. For animal products and other fomites, the criteria were: (1) whether the product has been shown or suspected to transmit FMDV to animals; (2) length of time that the virus survives in or on the product; and (3) whether the product is intended for direct use in animals.

Sources were reported for 627 of more than 880 primary FMD outbreaks reported worldwide from 1870 through 1993. Almost 66 percent of the outbreaks with reported sources were attributed to FMD-contaminated meat, meat products, or garbage; 22 percent to airborne transmission or birds; 6 percent to livestock importations; 4 percent to contaminated objects or persons; and 3 percent to vaccines. Over the last 25 years (since 1969), however, the most common sources have been imported animals and improperly inactivated vaccines. In North American and Caribbean nations, most outbreaks have been caused by imported animals or by imported meat or garbage.

Ninety-nine (99) animals were identified as possible sources of FMDV. Of those, 31 were categorized as a high hazard, 50 as moderate, and 18 as low. Animals that received a high hazard ranking included domestic pigs, wild and exotic deer, llamas, hedgehogs, humans, ticks and biting flies. Swine can be important initiators and amplifiers of FMD and have been associated with airborne spread of outbreaks. Deer have been shown to transmit FMDV to other animals and llamas have demonstrated experimental transmission under natural conditions. Hedgehogs and humans could play a role in FMDV transmission as mechanical carriers. Some species of biting flies and ticks can transmit FMDV through bites and can be long-term carriers.

A total of 97 animal products or fomites that could harbor FMDV were categorized as to hazard, although few animal products are likely to be totally FMD-hazard-free. Fifty-three (53) products or fomites were categorized as a high hazard, 23 as moderate, and 21 as low. Biologics were

considered a high FMD hazard because of direct use in animals and a history of improperly-inactivated FMD vaccine. Bovine semen also received a high hazard ranking because of demonstrated transmission of FMDV through artificial insemination and persistence of virus in collected samples. Hides and skins were given a high hazard ranking, as they have been suspected as a mode of FMDV transmission in at least one U.S. outbreak and can harbor potentially-infective virus for an extended period. The hazard for meat products ranges from low to high, depending on the types of tissue involved and the processing they undergo. Although FMDV may be carried in air over many meters, long-distance airborne (wind) transmission depends on highly specific atmospheric conditions. Thus, FMDV transmission via wind received a moderate hazard ranking.

INTRODUCTION

Foot-and-mouth disease (FMD) is a highly contagious viral disease that affects primarily cloven-hoofed animals, often with serious economic consequences. Although FMD rarely causes the death of mature animals, the disease can result in dramatic decreases in livestock productivity and loss of foreign markets for livestock and animal products.

The last known case of FMD in the United States was in 1929 (the last in North America was in Mexico in 1954) and a variety of regulations designed to reduce the risk of reintroducing the disease are now in place. First, the entry of susceptible species of animals from countries with FMD is strictly regulated. In addition, meats, hides, bones, animal casein, glands, and other products considered potentially dangerous are allowed entry to the United States only under prescribed processing conditions (1). Additional testing of such products is sometimes required once they reach the United States. Finally, U.S. research and diagnostic work with live foot-and-mouth disease virus (FMDV) is permitted only in an island-based laboratory.

The United States supports FMD initiatives in Panama and Colombia. In Panama, the United States provides funds for a control zone and diagnostic laboratory services in the event FMD is introduced from South America. To date, no country in Central America has reported a case of FMD. In Colombia, funding provided by the United States has been used to help eradicate FMD from much of the Darién region bordering Panama. That FMD-free zone will help prevent movement of FMD from South America into Panama in the event that the Pan American Highway is ever completed.

Concerns over FMD persist for several reasons. First, the economic consequences of an unchecked FMD outbreak in the United States would be great -- estimated in 1979 to be more than $12 billion in the first 15 months (2). Similar studies for Canada in 1987 suggested that the economic consequences for even a small outbreak of FMD would be in the order of $2 billion (3). Second, changes in trade and sanitary regulations may increase the possibility of reintroduction of FMD. Third, the capability to deliver animals and animal-origin products from farther distances is increasing and the transit time is decreasing. Fourth, trade by air and by sea around the incomplete section of the Pan American Highway between South and Central America is increasing. Finally, because of the length of time since the last case of FMD was seen in North America, there are few U.S. livestock producers or animal health workers with direct experience in the recognition and handling of the disease.

This report is one of three components needed to evaluate the risk of introduction of FMD to countries in North America, including Central America and especially the United States. The many possible modes of transmission associated with FMDV are summarized and a methodology to rank modes of transmission by relative biological hazard is developed and applied. Two other components are to be developed. APHIS's International Services will research and analyze FMD prevalence, control programs, and disease trends in South American countries reporting the disease. APHIS's Policy and Program Development will analyze the movement of commodities from South to North America. Together, these three components will provide the basis for formulating a strategic approach to address the risk of FMD.

BACKGROUND

Though many species of cloven-hoofed animals are susceptible to the seven types and dozens of subtypes of FMDV, those of economic significance include cattle, sheep, swine, goats, domestic water buffalo, farmed game animals, llamas, alpaca, reindeer, and camels. FMD has been found to

occur naturally, although not commonly, in many other mammals such as elk, deer, moose, hedgehogs, porcupines, rats, cats, and dogs. Transmission of FMDV from such mammals appears to be rare (4). Humans can become infected with FMDV, although authenticated cases are few. At least 16 other types of animals can be experimentally infected with FMDV. Horses are resistant to infection with FMDV.

Although the primary route of transmission of FMDV among animals is via respiratory aerosols, the virus is present in all physiologic secretions of infected animals. Aerosol transmission usually involves animals in close proximity; however, evidence suggests that airborne transmission may occur over long distances. High concentrations of FMDV can be detected in saliva hours before clinical lesions appear and in feces and milk up to 4 days before clinical signs occur. Thus, infected animals not yet showing clinical signs of the disease may be efficient transmitters of the virus (1).

Transmission may also occur via ingestion of contaminated feed, animal products, or water, as well as by exposure to semen and biological products such as vaccines that contain incompletely inactivated FMDV. Humans, birds, ectoparasites, and other fomites can also play a role in transmission of the virus (1).

After an incubation period that can range from 24 hours to 21 days, the classical clinical presentation of FMD involves salivation and lameness caused by vesicle formation in the mouth and on the feet. Rupture of the vesicles leaves painful erosions that bleed easily. Sloughing of the hooves, marked difficulty in eating, chronic mastitis, and other secondary infections may occur. Prognosis for recovery is favorable in all but very young animals, where mortality can exceed 50 percent (1).

Animals that have recovered from infection or were vaccinated and then exposed to FMDV may carry the virus in the soft tissues of the throat for variable periods of time, ranging up to 2.5 years in cattle and 5 years in African buffalo (5). There is recent evidence from Zimbabwe of transmission of FMDV from carrier African buffalo to cattle, 5 months after clinical disease in the buffalo (6,7). There is still only circumstantial evidence, however, that carrier cattle may transmit the virus, as experimental transmission has only been successful for up to about 8 days after clinical disease (1,8,9).

SOURCES AND LOCATIONS OF PRIMARY OUTBREAKS

To help assess the modes of FMDV transmission that could be involved in future FMD outbreaks, a search of the literature on the sources of past primary FMD outbreaks was performed. Such outbreaks were grouped by reported source. A source was considered to be the animal, product, fomite, or other vehicle that brought FMDV into direct contact with the animals that eventually developed FMD. Primary outbreaks were outbreaks new to a geographic area in terms of time period or FMDV type, not just secondary to previous cases of FMD in the area. Consequently, outbreaks in highly enzootic areas are usually not primary outbreaks unless they involve a non-enzootic FMDV type.

Foot-and-mouth disease is enzootic in Africa, Asia, and most of South America. Most of Europe is currently free of FMD, although primary outbreaks occasionally occur (e.g., Italy had an outbreak in 1993). North America, Japan, and Australia have all been free of the disease for many decades. New Zealand and Central America (from Guatemala to Panama) have never experienced FMD.

Foot-and-mouth disease first reached the New World in 1870 via cattle imported from England (4). Of 21 primary outbreaks of FMD in North America or the Caribbean, 16 had a source of the virus reported. The most common sources were imported animals and imported meat, meat products, or garbage (Table 1).

Outbreaks of FMD in Great Britain have been extensively documented, with at least 725 primary outbreaks between 1908 and 1981. Almost three-fourths of the 523 outbreaks with known sources were caused by contaminated meat, meat products, or garbage. A major epizootic in England and Wales from 1967-1968 was linked to frozen lamb carcasses from Argentina. Virtually all of the remaining outbreaks were reportedly caused by airborne (wind) spread or migrating birds (Table 2).

Worldwide, over 880 primary FMD outbreaks have been reported from 1870 through 1993 (Tables 3 through 9). Of the 71 percent (627) that had a source reported, almost 66 percent (47 percent of all outbreaks) were attributed to contaminated meat, meat products, or garbage; 22 percent to airborne spread or migrating birds; 6 percent to livestock importations; 4 percent to contaminated objects or persons; 3 percent to contaminated or incompletely inactivated vaccines; and less than 1 percent to wildlife (Table 10).

Further analysis of the data shows that sources of outbreaks in the last 25 years have been quite different than they were prior to 1969 (Table 11). A much larger share of all primary outbreaks was caused by livestock importations and vaccines during the last 25 years, with a much smaller share caused by meat or garbage and by airborne spread or migrating birds.

Of the 411 outbreaks that were attributable to infected meat, meat products, or garbage, all but 16 occurred more than 25 years ago (Table 3). They included the last U.S. outbreak (Los Angeles, 1929) and the largest FMD epizootic in the UK (1967-1968). In the latter case, farm dogs dragged bones from frozen lamb carcasses imported from Argentina to pigs on the farm. Over 53 percent (290) of the 540 primary outbreaks that occurred in the UK between 1938 and 1953 were attributed to contact with waste food. In addition, the last Canadian outbreak in 1952 may have been caused by a sausage brought into Canada by an immigrant German worker. Most of the 16 outbreaks caused by infected meat or garbage in the last 25 years (1969-1993) occurred in Europe, the latest reported in Italy in 1979.

Airborne (wind) transmission, and possibly migrating birds, as a source of primary FMD outbreaks has been extensively postulated, if not conclusively proven. Most (133/139) of the outbreaks considered to have been caused by airborne transmission occurred prior to 1969 and over 95 percent of the outbreaks have been in Great Britain (Table 4). This includes the outbreaks on Jersey and the Isle of Wight in 1974 and 1981 that were felt to have been caused by airborne spread from outbreaks in France. Sweden had an outbreak attributed to airborne spread of virus that escaped from a laboratory in Denmark. The only primary outbreaks outside of northern Europe attributed to airborne transmission both occurred in Israel in 1985, where virus was postulated to have spread from wild boars in Jordan.

Livestock importations and transfrontier (across country border) movements of livestock have been frequent culprits in the introduction of FMD into countries worldwide. Such movements have been documented as a source of primary outbreaks since the 1800's and they continue to cause outbreaks despite more rigorous quarantine programs. In fact, of the 35 outbreaks caused by livestock movement, 25 have occurred in the last 25 years (Table 5). Although quarantines have been established in many countries to prevent the introduction of FMD by imported stock, problems may arise from illegal importations, carrier animals, and animals such as sheep and goats that do not readily show lesions.

Contaminated objects or persons accounted for an additional 22 primary outbreaks of FMD (Table 6). Only 3 of those outbreaks occurred in the last 25 years. Eleven primary outbreaks occurred in Switzerland between 1947 and 1953 as a result of imported fodder and the former USSR had four outbreaks from sources as diverse as parcel packing straw and infected "carriages." In addition, the U.S. Department of Agriculture's Plum Island Animal Disease Center on Plum Island, NY, reported an incident in 1978 where FMD was discovered in steers housed outside the biocontainment laboratory. The fact that only one pen of animals was infected suggested that the outbreak was caused by direct mechanical transmission rather than an airborne route (10). FMD did not spread beyond the island, thus the FMD-free status of the United States was not affected.

There have been 20 primary FMD outbreaks attributed to improperly inactivated FMD vaccine or FMD-contaminated vaccine (Table 7). All of the 17 outbreaks since 1969 occurred in Europe, most recently in the Federal Republic of Germany in 1987. The 1902 and 1908 outbreaks in the United States were traced to contaminated vaccinia vaccine from Japan.

Although wildlife can serve as a reservoir for FMD, it has not often been implicated as a source for primary outbreaks. The three documented outbreaks (one in South Africa, one in Zimbabwe, and one in the former USSR) were caused by wildlife migration or occurred adjacent to FMD-enzootic wildlife reserves (Table 8).

HAZARD CATEGORIZATION OF MODES OF VIRUS TRANSMISSION

Modes of FMDV transmission were evaluated as to the potential hazard they might present in terms of the presence and length of persistence of the virus. This evaluation considered only the biological hazard of various modes of transmission. There was no direct consideration given to factors such as specific region of origin; likelihood that a given product or animal might be transported to North America; specific destination within North America; likelihood of exposure to susceptible animals; the length of transit, quarantine, or other time that might pass before exposure; or likelihood that an exposed animal might develop an infection. All such factors must be considered when attempting to determine the overall FMD threat that might be posed to countries in North America by a particular type of animal or product.

The methodologies for hazard categorization, described separately below for live animals and for animal-origin products or other fomites/vehicles, are conservative. That is, the methodologies tended to categorize animals or products and other fomites into the highest reasonable hazard category. For example, when information on FMDV transmission or carrier status (or virus survival) was unknown, it was assumed that the possibility of transmission did exist or that the carrier status (or virus survival) was more than "none." This approach was unlikely to underestimate the hazard of any of the animals or products considered and probably overestimated the hazard associated with some animals or products.

When information about a specific animal, product, or fomite was unknown or could not be found, no assumptions were made based on information known about animals of similar taxonomic classification, similar products, or other fomites. For example, although domestic swine are known to transmit FMDV to other animals, it was not assumed that wild boars also transmit FMDV because no direct evidence of such transmission is known. In such situations, a given animal, product, or fomite may have been placed in a different hazard category than an otherwise similar animal, product, or fomite.

Hazard categories for live animals and for animal products and other fomites were determined using different categorization methodologies. Thus, hazard categories for live animals should not be equated to the corresponding hazard categories for products or fomites, nor vice versa.

■ Live Animals

There are many animals that could possibly transmit FMDV (Table 12). For each type of animal it is important to consider whether it can be a natural host or only an experimental host, whether or not it has been shown to transmit FMDV to other animals, and the length of any carrier status.

Methodology for Hazard Category Determination

A hazard category for each type of live animal that is a possible transmitter of FMDV was derived according to the methodology described below. These categories reflect the inherent, potential hazard that one type of animal may pose as a source of FMDV relative to other types of live animals, assuming that all such animals are exposed to FMDV.

Three questions were used to determine hazard categories for live animals.

1) Has the animal been a natural host? Possible answers were "yes" (has been a natural host) or "no" (has only been an experimental host). We defined natural hosts as animals that have acquired FMD in a natural setting or have been experimentally infected in a way that could occur naturally. Experimental hosts are animals that have only been infected in ways that are unlikely to occur naturally (e.g., inoculation).

2) Has the animal been shown or suspected to transmit FMDV to other animals? Possible answers were "yes," "unknown," or "no." In order to be "no," transmission had to have been tried and found not to occur. Transmission shown only under experimental conditions that would be unlikely to occur naturally was considered to be equivalent to "unknown" transmission.

3) What is the length of FMDV carrier status in the animal? Possible answers were "long" (14 days or more), "short or unknown" (more than 0 but less than 14 days, or, no information), or "none" (information indicates that a carrier state does not occur). Fourteen days was chosen to represent the maximum probable transit time for live animals being shipped internationally. Thus, animals capable of carrying FMDV for at least 14 days would have the most potential for bringing virus into an FMD-free country (barring a quarantine period) and therefore represent a greater hazard.

Animals were assigned to a hazard category (low, moderate, or high), based on the answers to the above three questions, as follows (Figure 1):

Low: experimental host,
or,
natural host with no transmission and length of carrier status is "none," "short," or "unknown"

Moderate: natural host with no transmission and "long" carrier status,
or,
natural host with "unknown" transmission and length of carrier status is "none," "short," or "unknown"

High: natural host and transmission is "yes,"
or,
natural host with "unknown" transmission and "long" carrier status

Results of Hazard Categorization for Live Animals

Of the 99 animals identified as possible sources of FMDV, 31 were categorized as high hazards, 50 as moderate, and 18 as low (Table 12). Some of these animals are discussed below.

Wild Bovidae

Many of the types of Bovidae that may transmit FMDV are nondomesticated (Table 12). All such wild bovids were assigned to either moderate or high hazard categories. Those assigned to the high category were species from which transmission of FMDV has been confirmed.

Although there have been few confirmed primary outbreaks caused by wild game, circumstantial evidence suggests that such animals may be a source of outbreaks among cattle in countries where wild game and domestic cattle often share grazing land and watering holes (11). In a large survey conducted between 1965 and 1969, 1,323 samples of serum were collected randomly from 39 species, primarily in Zimbabwe (formerly Rhodesia). Significant FMDV antibody titres were found in 16 species, all cloven-hoofed animals (Table 12) (12). Of particular interest is the African buffalo; of the 116 animals tested, 77 had positive antibody titres. African buffalo often do not show clinical signs and may carry the virus for long periods (5 years). A study in an area in which FMD had not been recorded for 25 years found 14 of 34 buffalos with significant antibody titres (11). In addition, recent studies involving nucleotide sequencing of the virus support the belief that wild bovids, particularly African buffalo, may play a role in the transmission of FMDV to cattle (6,7).

Suidae

Domestic pigs were assigned a high hazard category. They play an important role in the epizootiology of FMD as initiators and amplifiers. They can act as initiators of FMD by the consumption of infected garbage. Pigs serve as amplifiers of the virus because they can excrete aerosols that contain up to 3,000 times more virus than produced by an equal number of cattle or sheep (Table 12). Many outbreaks linked to airborne spread are thought to have originated from domestic pigs. One characteristic that distinguishes pigs from cattle and sheep is that they appear to harbor the virus only during clinical stages of the disease and therefore do not act as carriers (13). Some other species of Suidae have been known to become infected and show clinical signs of FMD, but it is not known if other such species can carry the virus subclinically. Information is also lacking on transmission of virus from other Suidae.

Cervidae

Most deer, including white-tailed and mule deer like those found in North America, were assigned a high hazard category because of demonstration of FMDV transmission. At least one white-tailed deer remained a carrier of FMDV for 11 weeks after infection (Table 12). Exotic deer, including red, sika, and fallow, have been gaining popularity for use on deer farms or game ranches. Such deer have been found to both acquire and transmit FMDV under natural conditions. There is no information on transmission from other cervids such as moose and elk. Accordingly, those cervids were placed in the moderate hazard category.

■ Animal-Origin Products and Other Fomites or Vehicles

Many animal-origin products and other fomites or vehicles can serve as possible modes of FMDV transmission. For each product or fomite, consideration was given to specific processing, storage, or other conditions. Therefore, when a given product was processed in a different way or a fomite was evaluated under different conditions, it was considered as if it were a different product or fomite. A total of 76 products (15 nonfood and 61 food) and 21 fomites were identified (Tables 13 and 14).

Methodology for Hazard Category Determination

A hazard category for each type of product or other fomite that is a possible transmitter of FMDV was derived according to the methodology described below. These categories reflect the inherent, potential hazard that one type of product or fomite may pose as a source of FMDV relative to other types of products or fomites. It was assumed that products are derived from FMDV-infected animals and that fomites or other vehicles are in close contact with FMDV.

The three questions used to determine hazard categories for animal-origin products and other fomites or vehicles were:

1) Has the product or fomite been shown or suspected to transmit FMDV to animals? Possible answers were "yes," "unknown," or "no." In order for this to be "no," transmission had to have been tried and found not to occur.

2) What is the possible length of virus survival in the product (after processing) or on the fomite? Possible answers were "long" (14 days or more), "short or unknown" (more than 0 but less than 14 days or no information), or "none" (information indicates that there is no survival). Fourteen days was chosen to represent the maximum probable transit time for products shipped internationally. Thus, products or other fomites capable of harboring FMDV for at least 14 days would have the most potential for bringing virus into an FMD-free country (barring a quarantine period) and therefore represent a greater hazard.

3) Is the product or other fomite intended for direct animal use? Possible answers were "yes" (direct use in or with animals) or "no or indirect" (no animal use or indirect use only).

Products and fomites were assigned to a hazard category (low, moderate, or high), based on answers to the above three questions, as follows (Figure 2):

Low: no transmission,
or,
no virus survival

Moderate: transmission is "yes" or "unknown," length of virus survival is "short" or "unknown," and direct animal use is "no" or "indirect"

High: transmission is "yes" or "unknown" and length of virus survival is "long,"
or,
transmission is "yes" or "unknown," length of virus survival is "short" or "unknown," and direct animal use is "yes"

Llamas

Llamas were categorized as high hazard animals based on the results of experimental transmission of FMDV under "natural" conditions, although such experimental work in llamas has yielded somewhat inconsistent results. One experiment showed that FMDV was transmitted from cattle to llamas, from llamas to swine, and from llamas to other llamas (14). Responses in the llamas ranged from generalized infection with mucosal lesions (oral and lingual) and severe lameness to no clinical signs. No virus was isolated from the oesophageal-pharyngeal (OP) fluid of infected animals after 7 days post-inoculation or post-contact.

In another study, none of 20 llamas exposed to pigs infected with FMDV types A or C developed clinical signs or yielded any virus from OP fluid or blood (15). Two of 10 llamas exposed to pigs infected with FMDV type O did develop mild lesions. After removal of the pigs, additional susceptible llamas and other domestic livestock were placed in contact with the initial group of 30 exposed llamas; all of the secondary exposure group llamas remained healthy and were negative for FMDV antibodies. The authors concluded that llamas are resistant to FMDV infection and that they harbor the virus in their OP region only for a short time.

Humans

Humans may acquire FMDV through various routes, the most important of which has probably been ingestion (drinking infected milk) (16,17). Airborne virus has also been linked with several human cases, as has direct contact with infected animals. However, the number of documented cases in humans is relatively small (only in about 40 cases has FMDV been isolated), indicating that humans are quite resistant to FMDV infection and that it is not a public health problem (16).

Whether or not one considers FMD to be a true zoonotic disease, humans can play a role as carriers or transmitters of FMDV and were categorized as a high hazard. Virus has been recovered from the nasal passage up to 36 hours after exposure. It is reported that virus can be isolated from humans with vesicles up to 14 days after the onset of disease (16,17). However, the most important form of transmission from humans to animals is mechanical, because virus can persist on clothing or shoes for at least 9 weeks (18).

Invertebrates

Although the role of flies and ticks in the epizootiology of FMD is not usually large, it has been demonstrated that ticks and some species of biting flies can transmit the virus through bites. Ticks, flies, and biting flies were categorized as high hazards, based either on transmission capability or long carrier status (whether mechanically or biologically). Houseflies can carry FMDV both externally and internally; whether they can transmit the virus is unknown. It is unlikely that the virus multiplies in the cells of invertebrates. However, experimental transovarial infection of a portion of a population of *Dermacentor* (*Anocentor*) ticks has been reported (11).

FMDV has also been transmitted to cattle experimentally by inoculating them with ground-up earthworms (11). Given the artificial nature of transmission and given that infected earthworms are not known to have been associated with any outbreaks, earthworms were placed in the moderate rather than the high hazard category.

Results of Hazard Categorization for Nonfood Products or Byproducts

Of the 15 nonfood products or byproducts identified as possible sources of FMDV, 12 were categorized as high hazards, 1 as moderate, and 2 as low (Table 13). Some of these products are discussed below.

Biologics

The primary role of biologics in the transmission of FMDV has been through the use of improperly inactivated FMD vaccine. Outbreaks have occurred primarily in Europe due to the use of formalin-inactivated vaccines (19). In the early 1900's other biologics were found to be contaminated with FMDV. Although it is less likely that problems with inactivation or contamination of vaccines could occur today given the techniques now used by most manufacturers, biologics were assigned to the high hazard category because of their intended direct use in animals and their history of FMDV transmission (Table 13).

Embryos and Semen

Because at least three experiments have shown that washed, zona pellucida-intact embryos taken from infected cows are not infective, they received a hazard classification of low (Table 13). In one study, infectivity was found neither in embryos collected during the acute stages of disease, nor in embryos taken from cows 21 days after infection (20). In another experiment, a total of 436 embryos were collected from 30 FMD viremic cows, 8 of which had FMDV in their reproductive tracts (21). All 287 of the embryos assayed for infectivity were negative. The other 149 embryos were implanted into susceptible recipients; all of the calves and recipients remained FMD-negative. A third study found that washed, zona pellucida-intact embryos from seropositive dams had no infectious virus present and that cows into which such embryos were implanted remained free of infection, as did the calves that developed from those embryos (22). The only study which showed infectivity associated with bovine embryos was one in which the embryos were exposed in vitro and were zona pellucida-free (hatched) (23).

Bovine semen was classified as having a high biological hazard (Table 13). FMDV has been found in semen as early as 12 hours after inoculation of bulls and as long as 42 days after contact exposure (13). In addition, heifers artificially inseminated with infected semen have developed FMD (11). In swine, FMDV has not been transmitted through artificial insemination even though semen from infected swine contains FMDV (24). Consequently, although further transmissibility studies in swine may be warranted, porcine semen was categorized as a low hazard.

Hides or Skins

FMDV remained infective in hides preserved by 4 conventional methods for varying lengths of time, all over 14 days (Table 13). The authors of the study noted that these experimentally observed time periods should not be considered maximum survival times (11). Further, imported hides were suspected of causing the 1914 outbreak in the United States, in which at least 22 states and the District of Columbia were affected (25). Untanned hides and skins are currently allowed entry into the United States if they are "hard dried," "pickled in a solution of salt containing mineral acid," or "treated with lime in such a manner and for such a period as to have become dehaired" (26). No studies were found in which the effect of such processing on FMDV was examined. Hides and skins were therefore given a hazard categorization of high.

Results of Hazard Categorization for Food Products

Of the 61 nonfood products identified as possible sources of FMDV, 25 were categorized as high hazards, 17 as moderate, and 19 as low (Table 13). The final categorization of a product was often determined by the specific processing conditions that the product underwent. That is, the same basic product may have different categorizations because of different methods of processing.

Meats

Hazard categories for meats ranged from low to high depending on the type of tissue and processing involved (Table 13). Virus survival in meat depends on whether the meat is only muscle tissue or if it contains fat, bone marrow, or lymph nodes. Lactic acid formation during rigor mortis inactivates the virus in chilled muscle tissue within 3 days. However, virus in lymph nodes, fat, or bone marrow can survive for much longer periods under the same conditions. Immediate freezing also dramatically extends survival time in muscle tissue, although the virus is destroyed within 1 hour after thawing because of a rapid decrease in pH (27).

The effect of different meat processing methods on FMDV inactivation is variable. Mincing, for example, distributes lactic acid throughout the product, such that the virus is more readily inactivated in tissues (e.g., fat) that would otherwise have higher survival times (28). Temperatures above 155°F (68°C) can destroy the virus, but destruction depends on the combination of temperature and length of treatment used (29).

The virus can also survive for significant periods of time in some salt-cured meat products. Salted bacon is reported to have been found with FMDV for up to 183 days (30). Parma hams, produced in Italy through a salt-curing and aging process, can harbor FMDV for several weeks, although virus has not been found at 170 days or more of the curing process (31). Because a 12-month curing process is required for such hams, the finished product was categorized as a low hazard. Salted and dry-cured Iberian and Serrano hams from Spain may also be found with FMDV several weeks into curing, but maximum survival did not exceed minimum curing times (32). Thus, such hams were also placed in the low hazard category.

Milk

Large amounts of FMDV may be secreted by lactating cows during the preclinical phase of FMD infection and may persist in the mammary tissue of convalescent cows. FMD-infected milk can be a source of contamination to the milking parlor, milking equipment, animal holding areas, and other livestock fed surplus milk. In addition, high virus concentration in milk could be unknowingly delivered to processing plants and distributed prior to FMD detection. It is believed that aerosolized FMDV from bulk milk tanker trucks played a role in the spread of FMD in the UK in 1967-1968 (33).

In general, whole and skim milk were categorized as low or moderate hazards, depending on the exact processing time and temperature utilized (Table 13). The U.S. Public Health Service's recommended minimum time and temperature values for grade A pasteurized milk are 72°C for 15 seconds or 63°C for 30 minutes (34). These requirements are inadequate to destroy FMDV in milk.

The thermal death curve for FMDV in milk (Figure 3) was derived from results of several studies on inactivation of the virus under various combinations of time and temperature. Survival or inactivation of virus for about 3 dozen combinations was plotted to establish the curve. The curve was drawn so that time and temperature treatments on the right side of the curve may be expected to inactivate FMDV in milk; those on the left may or may not. In addition to time and temperature,

thermal inactivation of FMDV in milk may also be affected by factors such as viral content and pH. The thermal death curve presented does not account for variations in those factors.

Cheese

Virus survival in cheeses is determined by the manufacturing process. As mentioned above, heating the milk beyond certain temperatures or times will destroy the virus, as will a low pH. Although a pH of 6.2 or below is enough to kill the virus in meat, a more acidic environment is needed to kill the virus in cheese products because the protein and fat in milk are thought to be protective (27). FMDV has survived for at least 21 days in a cheese product with a pH as low as 5.2 (35).

Virus was found in some cheeses (e.g., cheddar) during the manufacturing/curing process, but not at a later point (Table 13). However, because information about the usual commercial curing times was not provided, it is not known if virus can survive commercial processing. Although cheddar cheese was categorized as a moderate hazard, it is possible that more information on curing times and survival beyond those times could have warranted the assignment of a high hazard.

Results of Hazard Categorization for Other Fomites or Vehicles

Of the 21 fomites or vehicles identified as possible sources of FMDV, 16 were categorized as high hazards, 5 as moderate, and none as low (Table 14).

Air (Wind)

Animal-to-animal airborne spread of FMD via aerosols was considered likely as early as the 1930's (36,37). Since that time it has been established that transmission of FMDV via aerosol over a distance of several meters does occur (8,36). It has also been shown that the dose of FMDV required to infect cattle via respiratory inhalation is lower than that required for infection through oral ingestion (38).

The possibility of wind transmitting aerosolized FMDV over distances of much more than a few meters has received attention since the late 1960's and early 1970's (36,37,39). Most of the interest in this mode of transmission has been related to the possibility of spread over the sea, as from the continent of Europe to Great Britain, although transmission over land has also been studied (37,40,41).

Meteorological conditions play a major role in both the survival of virus and in its dispersion. Relative humidity is the most important factor in virus survival (42). If the relative humidity stays above 60 percent, the virus survives for many hours. Sunlight does not have a strong effect on FMDV survival (43). Conditions that cause minimal dispersion of a virus plume favor long-distance spread of the virus (42). The best conditions for minimal dispersion are low wind speed and a stable atmosphere with few convection currents. Precipitation probably does not contribute directly to long-distance spread of virus.

Quantitative models have been developed to examine the possibility of airborne FMDV transmission over distances of less than 10 km and also for greater distances of 60 km or more (41,44,45). Such models consider factors such as quantity of virus emitted at a source, virus survival, and particle dispersion and deposition (42,44).

Verification of models has primarily been through application to past outbreaks. Such applications have shown that the long-distance transmission of FMDV is plausible under certain conditions. These conditions tend to be met more often over the sea, where high relative humidity, steady

winds, minimal convection, and lack of topographical obstructions are more common. Transmission over distances as great as 250 km over sea and 60 km over land has been suggested (37,44).

Thus, although it is plausible that long-distance airborne transmission of FMDV occurs, the conditions required are highly specific and there are probably few times when all of the conditions are met. One review of atmospheric conditions between France and the UK over a 10-year period found that the conditions needed for long-distance transmission occurred only once (41). Those conditions happened to coincide with a large source of virus emission in France and with outbreaks of the same virus type on Jersey and the Isle of Wight up to 250 km away in the UK.

In general, the hazard of long-distance airborne transmission of FMDV is considered to be moderate compared to the hazard of other fomites or vehicles (Table 14). The hazard of airborne transmission from South America to Central America may, in fact, be less than moderate because of the meteorologic and geographic conditions that normally exist in those regions.

SUMMARY

There are many possible modes of transmission of FMDV. A total of 99 animals and 97 animal-origin products or other fomites (15 nonfood products, 61 food products, and 21 other fomites) were identified in this report. Although each mode of transmission has some potential to transmit FMDV to domestic livestock, differences exist in their likelihoods of so doing. Even though there are few if any bovine-origin products that have no FMD hazard associated with them, the level of that hazard and the probability of actual FMDV transmission associated with each product are the issues that must be considered in an assessment of risk. Such an assessment must also take into consideration additional factors such as specific region of origin, specific destination, length of transit, and quarantine procedures, in order to estimate the risk of FMDV transmission.

A literature review found that 71 percent of over 880 primary outbreaks of FMD reported around the world since 1870 had a known or suspected source. About 66 percent of primary outbreaks with reported sources (47 percent of all primary outbreaks) were attributed to meat, meat products, or garbage. Worldwide, sources of outbreaks in the last 25 years have been quite different than they were prior to 1969, with a much larger share of all primary outbreaks caused by livestock importations and vaccines during the last 25 years and a much smaller share caused by meat or garbage and by airborne spread or migrating birds. In North America and the Caribbean, animal importation was the most commonly reported cause among the 16 primary FMD outbreaks in which a source was identified.

A set of criteria was used to differentiate between types of animals or products that pose the highest biological hazard in terms of serving as a source of FMDV and those that pose a lower hazard. Three general assumptions were made: (1) live animals are exposed to FMDV; (2) products are derived from FMDV-infected animals; and (3) fomites or other vehicles come in contact with FMDV. The criteria that were used to rank live animals were: (1) whether the animal is a natural or experimental host; (2) whether the animal has transmitted FMDV to other animals; and (3) length of carrier status. For animal products and other fomites, the criteria were: (1) whether the product has been shown or suspected to transmit FMDV to animals; (2) length of time that the virus survives in or on the product; and (3) whether the product is intended for direct use in animals.

Of the 99 animals identified as possible sources of FMDV, 31 were categorized as high hazards, 50 as moderate, and 18 as low. In addition to traditional livestock such as cattle, sheep, and pigs, animals in the high hazard category include African buffalo, white-tailed deer, and hedgehog.

Of the 97 animal products or other fomites identified, 53 were categorized as high hazards, 23 as moderate, and 21 as low. Of 15 nonfood products identified, 12 were categorized as high hazard, 1 as moderate, and 2 as low. Among the high hazard nonfood products were hides or skins and bovine semen. Of 61 food products, 25 were high, 17 moderate, and 19 low. Hazard categories for food products are largely determined by the specific processing conditions that the products undergo. Of 21 fomites, 16 were high and 5 moderate. High hazard fomites include clothing, shoes, and garbage.

It should be emphasized that the proposed hazard categorizations do not represent the risk of an animal or product introducing FMDV from South America into North America. The hazard categorizations do provide a basis for better understanding the possible sources of FMDV and a point for beginning a complete analysis of the risk of FMDV transmission.

Table 1. Primary Outbreaks of Foot-and-Mouth Disease in North America and the Caribbean			
Year	**Point of Origin**	**Source**	**Reference**
1870	Canada (Montreal, PQ)	Cattle imported from England	46
1870	USA (Oriskany, NY)	Spread from Canada (cattle)	1,46,47,48
1875	Canada (Toronto, ON)	Imported sheep	49
1881	USA (New York, NY)	3 lots of cattle imported from England	25,48
1884	USA (Portland, ME)	Imported animals (no spread)	25,48
1902	USA (Chelsea, MA)	Vaccinia vaccine from Japan	25,48
1908	USA (Detroit, MI)	Vaccinia vaccine from Japan	25,48
1914	USA (Niles, MI)	Imported tanning materials (hides), or, hogs fed offal and trimmings from a packing house that handled foreign meats	25,48
1924	USA (Houston, TX)	Sailors from ships carrying live animals	25,47,48
1924	USA (Vallejo, CA)	Ship's garbage fed to swine	25,47
1925	Mexico (Frontera, Tabasco)	Cattle from a "banana boat"	48
1929	USA (Los Angeles, CA)	Argentinean meat scraps from the cruise ship "City of Los Angeles" fed to hogs	47
1946	Mexico (Veracruz)	Zebu cattle from Brazil (after several months quarantine)	9,46,48
1952	Canada (Regina, SK)	Sausage or clothing from German immigrant farm worker	49,50,51
1953	Aruba	No information	52
1953	Martinique	No information	52
1953	Mexico (Gutierrez Zamora, Veracruz)	Carrier animal from 1946-1952 Mexico outbreak?	9,48
1957	Curacao	No information	52
1961	Curacao	No information	53
1964	Guadeloupe	No information	53
1978	USA (Plum Island, NY)	"Mechanical" escape from research laboratory (no spread)	10

Table 2. Primary Outbreaks of Foot-and-Mouth Disease in Great Britain			
Year(s)	**Location**	**Source**	**Reference**
1908	Edinburgh, Scotland	Imported hay	47
1923-1924	Major outbreak	Unknown	54
1938-1953	540 outbreaks	290 contact with waste food; 88 birds / wind; 162 unknown	55,56
1954-1966	175* outbreaks	95 imported meat & wrappings; 41 birds / other origins; 39 unknown	54
1960	Pirbright	Airborne escape from Animal Virus Research Institute	11,57
1966	Northumberland	Meat from overseas	58
1967	Pirbright	Airborne escape from Animal Virus Research Institute (no spread)	11
1967	Warwickshire	Pigs fed unboiled swill containing meat scraps	59
1967-1968	Spread from Oswestry, Shropshire, through England and Wales	Linked to frozen lamb carcasses imported from Argentina; dogs on the initial farm dragged carcass bones to pigs	54,60
1974	Jersey	Airborne from Normandy, France, outbreak of the same type	45
1981	Isle of Wight	Airborne from outbreak of same serotype in swine in Brittany, France	44
1981	Jersey	Airborne from outbreak of same serotype in swine in Brittany, France	44

* 2 outbreaks listed elsewhere in Table 2 have been subtracted from original total of 177

Table 3. Primary Outbreaks of Foot-and-Mouth Disease Caused by Feeding Meat, Meat Products, or Garbage			
Year(s)	**Location**	**Comment**	**Reference**
1914*	USA (Niles, MI)	Hogs fed offal and trimmings from a foreign meat packing house, or, imported tanning materials (hides)	25,47
1924	USA (Vallejo, CA)	Ship's garbage fed to swine	25,47
1929	USA (Los Angeles, CA)	Argentinean meat scraps from cruise ship fed to hogs	47
1938-1953	UK	290 outbreaks due to contact with waste food	55
1949-1951	Switzerland (central)	Vegetable (salsify) refuse given to pigs without boiling	61
1952*	Canada (Regina, SK)	Sausage (or clothing) from German immigrant worker	49,50,51
1954-1962	UK	95 outbreaks	54
1958	USSR (Irkutsk)	Byproducts of meat packing plants in Altajskaya	62
1966	UK (Northumberland)	Meat from overseas	58
1967	UK (Warwickshire)	Pigs fed unboiled swill containing meat scraps	59
1967-1968	UK (Shropshire)	Frozen lamb carcasses from Argentina	54,60
1968	Switzerland		63
1969	Belgium		63
1969-1970	Greece	2 outbreaks	63
1969	Switzerland		63
1971	Belgium		63
1972	Greece	2 outbreaks	63
1975	Italy		63
1975	Malta	Swine fed infected swill/garbage from docks or airport	64
1976	Fed. Rep. of Germany		63
1977	Greece		63
1977-1979	Italy	4 outbreaks	63
1977	Morocco	Meat from South America	65

* outbreak had more than one reported source and therefore is also listed in Table 6

Table 4. Primary Outbreaks of Foot-and-Mouth Disease Caused by Airborne (Wind) Spread or Migrating Birds			
Year(s)	**Location**	**Comment**	**Reference**
1938-1953	UK	88 outbreaks attributed to airborne route or birds	55,56
1956-1959	UK	41 outbreaks attributed to birds or other routes	54
1960	UK (Pirbright)	No air filtration apparatus on laboratory; virus found 2 miles downwind	11,57
1966	Denmark (Zealand)	Accidental release from laboratory	45,57
1966	Sweden (Skaane)	Airborne from Denmark (after laboratory escape)	45
1967	UK (Pirbright)	Air filtration system damaged; no spread beyond laboratory	11
1974	UK (Jersey)	Airborne from Normandy, France	45
1981	UK (Isle of Wight)	Airborne from swine in Brittany, France	44,63
1981	UK (Jersey)	Airborne from swine in Brittany, France	44,63
1982	Denmark		63
1985	Israel (Yizrael)	Kibbutz Geva outbreak in dairy sheep; airborne from Jordan	66,67
1985	Israel (Yizrael)	Ramot Yissakhar outbreak in gazelles; airborne from Jordan	66,67

Table 5. Primary Outbreaks of Foot-and-Mouth Disease Caused by Livestock Importations or Transfrontier Movements			
Year(s)	**Location**	**Comment**	**Reference**
1870	Canada (Montreal, PQ)	Cattle imported from England	46
1870	USA (Oriskany, NY)	Spread from Canada (cattle)	1,46,47,48
1871	Australia (Sydney)	12 breeding stock cattle on the ship "Parramatta"	68
1872	Australia (Melbourne)	Bull passed quarantine, showed signs 1 month later	68
1875	Canada (Toronto, ON)	Imported sheep	49
1881	USA (New York, NY)	3 lots of imported cattle	25,48
1884	USA (Portland, ME)	Imported cattle	25,48
1925	Mexico (Frontera, Tabasco)	Cattle from a "banana boat"	48
1929	USSR (Irkutsk)	Breeding cattle from Mongolia	62
1946-1952	Mexico (Veracruz)	Zebu cattle from Brazil (after several months quarantine)	46,48
1969	Spain		63
1970	Greece		63
1972	Greece		63
1972	Spain		63
1973	Malaysia		69
1973	Turkey		63
1975	Tunisia		63
1977	Algeria		63
1977	Morocco		63
1977	Netherlands		63
1978	France		63
1978	Malta		63
1978	Yugoslavia		63
1979	Kuwait	Buffaloes from India	70
1980	Portugal		63
1981	France		63
1983	Morocco	Sheep from Spain	55,63
1984	Greece		63
1989	Tunisia		63
1990	Algeria		63
1990	Morocco		63
1990	Yemen	Cattle from eastern Africa	71
1992	Malaysia	2 outbreaks	72
1993	Italy (Potenza and Veneto)	Cattle from Croatia / Slovenia	73

Table 6. Primary Outbreaks of Foot-and-Mouth Disease Caused by Contaminated Objects or Persons			
Year(s)	Location	Comment	Reference
1908	Edinburgh, Scotland	Imported hay	47
1914*	USA (Niles, MI)	Imported tanning materials (hides), or, hogs fed foreign offal	25,47
1924	USA (Houston, TX)	Sailors from ships carrying live animals	25,47,48
1947-1953	Switzerland	11 outbreaks; imported fodder	61
1952*	Canada (Regina, SK)	Clothing (or sausage) from German immigrant farm worker	49,50,51
1960	USSR (Irkutsk)	Infected "carriages" from west Siberia	62
1960	USSR (Irkutsk)	Students visiting from Ukraine	62
1963	USSR (Irkutsk)	Straw from Kazakhstan used as parcel packing	62
1967*	USSR (Irkutsk)	Forest workers (or steppe antelope) from Kazakhstan	16,62
1978	USA (Plum Island, NY)	Mechanical escape from research laboratory (no spread)	10
1981	Greece		63
1993	Russia (Vladimir)	Laboratory worker	73

* outbreak had more than one reported source and therefore is also listed in Table 3 or Table 8

Table 7. Primary Outbreaks of Foot-and-Mouth Disease Caused by Vaccines			
Year(s)	Location	Comment	Reference
1902	USA (Chelsea, MA)	Vaccinia vaccine from Japan	25,47
1908	USA (Detroit, MI)	Vaccinia vaccine from Japan	25,47
1968	Denmark		63
1969	Czechoslovakia		63
1970	Denmark		63
1972	Fed. Rep. of Germany	2 outbreaks	63
1972	Hungary		63
1974	Belgium		63
1974	Fed. Rep. of Germany		63
1975	Greece		63
1976-1977	Fed. Rep. of Germany	2 outbreaks	63
1976-1977	German Dem. Rep.	2 outbreaks	63
1978	Switzerland		63
1979	Spain		63
1980	Fed. Rep. of Germany		63
1980	Switzerland		63
1987	Fed. Rep. of Germany		63

Table 8. Primary Outbreaks of Foot-and-Mouth Disease Caused by Wildlife			
Year	Location	Comment	Reference
1967*	USSR (Irkutsk)	Migrating steppe antelope (or forest workers) from Kazakhstan	16,62
1983	South Africa	Impala from Kruger National Park infected adjoining dairy cattle	74
1989	Zimbabwe	Buffalo probable source	75

* outbreak had more than one reported source and therefore is also listed in Table 6

Table 9. Primary Outbreaks of Foot-and-Mouth Disease with Unknown Sources			
Year(s)	Location	Comment	Reference
1893-1894	Denmark		46
1923-1924	Major UK outbreak		54
1938-1953	UK	162 outbreaks	55
1953	Aruba		52
1953	Martinique		52
1953	Mexico (Gutierrez Zamora, Veracruz)	Carrier animal from 1946-1952 Mexico outbreak?	9,48
1955-1966	UK	39 outbreaks	54
1957	Curacao		52
1961	Curacao		53
1964	Guadeloupe		53
1968	Czechoslovakia		76
1968	Romania		76
1968	Yugoslavia		76
1969	Poland		76
1978	Fed. Rep. of Germany		63
1978	Libya		63
1979	France		63
1979	Tunisia		63
1980	German Dem. Rep.		63
1981	Austria		63
1981	France		63
1981	Italy (Modena)	2 outbreaks	63
1981-1983	Spain	4 outbreaks	63
1982	Fed. Rep. of Germany		63
1982	German Dem. Rep.		63
1982	Libya		63
1982	Tunisia		63
1983	Denmark (Isle of Funen)	Virus not identical to 1982 outbreaks	77
1983	Netherlands		63
1983	Portugal		63
1984	Fed. Rep. of Germany	2 outbreaks	63
1984	Israel (northern border)	2 outbreaks	67
1984-1986	Italy	3 outbreaks (after 3 years with none)	54,63,78
1986	Spain		54,63
1987-1988	Fed. Rep. of Germany	2 outbreaks	63
1987	USSR		63
1988	Italy		63
1989	Libya		63
1989	Tunisia		63
1989	Zimbabwe	SAT2 in cattle	75
1990	Cote d'Ivoire		71
1990	Zambia		71
1991	Bulgaria	Middle East serotype	55
1991	Zimbabwe	SAT3 in cattle	75
1993	Brazil (south)	Swine; 20+ months since last outbreak	73
1993	Bulgaria	Middle East serotype	73

Table 10. Sources of Primary Outbreaks of Foot-and-Mouth Disease, Worldwide, 1870-1993	
Source [1]	Percent of Outbreaks [2]
Meat, meat products, or garbage	66
Airborne (wind) or migrating birds	22
Livestock importations	6
Contaminated objects or persons	4
Vaccines	3
Wildlife	<1

[1] known or suspected source

[2] outbreaks with a reported source (n=627)

Table 11. Sources of Primary Outbreaks of Foot-and-Mouth Disease, Worldwide, 1870-1968 vs. 1969-1993		
Source [1]	Percent of Outbreaks	
	1870-1968 [A]	1969-1993 [B]
Meat, meat products, or garbage	71	23
Airborne (wind) or migrating birds	24	9
Livestock importations	2	36
Contaminated objects or persons	3	4
Vaccines	1	25
Wildlife	<1	3

[1] known or suspected source

[A] outbreaks with a reported source (n=558)

[B] outbreaks with a reported source (n=69)

Table 12. Foot-and-Mouth Disease Virus in Live Animals

Animal	Comments	Natural or experimental host[1]	Transmission demonstrated?	Length of carrier status[2]	Hazard category	Reference
Class Mammalia, Order Artiodactyla, Family Bovidae						
antelope		natural	yes		High	12,16,46
antelope, roan	shows clinical signs	natural			Moderate	12,79
antelope, sable	shows clinical signs	natural			Moderate	11,79
bison		natural			Moderate	11,13
blackbuck	shows clinical signs	natural			Moderate	79,80
buffalo, African	less susceptible than cattle; clinical signs rare	natural	yes	5 years	High	5,6,46,75,81, 82
buffalo, water	shows clinical signs	natural			Moderate	11,47
bushbuck	shows clinical signs	natural			Moderate	12,79
cattle, domestic	shows clinical signs	natural	yes	2.5 years	High	5,11,16,18, 56,83,84
duiker		natural			Moderate	12
eland		natural			Moderate	12,46,47
gazelle, mountain	shows clinical signs	natural	yes		High	67
gemsbok	(Cape oryx)	natural			Moderate	11,12
grysbuck		natural			Moderate	12
hartebeest		natural			Moderate	11
impala	highly susceptible to aerosol; shows clinical signs	natural	yes	7 days	High	12,46,47,74, 79,85
kudu	shows clinical signs	natural			Moderate	12,46,79
nyala	shows clinical signs	natural			Moderate	79
reedbuck		natural			Moderate	12
springbok		natural			Moderate	11
steinbok		natural			Moderate	11
topi		natural			Moderate	12
tsessebe		natural			Moderate	12
waterbuck		natural			Moderate	11
wildebeest		natural			Moderate	12
yak		natural			Moderate	13
Class Mammalia, Order Artiodactyla, Family Bovidae, Subfamily Caprinae						
chamois		natural			Moderate	46
goat	shows clinical signs	natural	yes	9 months	High	5,11,13,47

Table 12 (cont.). Foot-and-Mouth Disease Virus in Live Animals

Animal	Comments	Natural or experimental host[1]	Transmission demonstrated?	Length of carrier status[2]	Hazard category	Reference
mouflon		natural			Moderate	11
sheep	shows clinical signs	natural	yes	9 months	High	5,11,13,18, 46,47
Class Mammalia, Order Artiodactyla, Family Camelidae						
alpaca	relatively resistant?; shows clinical signs	natural	yes		High	13,14,46,84
camel (bactrian?)	shows clinical signs?	natural	yes	35 days	High	11,14,46,47, 86
dromedary	shows clinical signs	natural		6 days	Moderate	11,87
llama	low susceptibility; shows clinical signs	natural	yes	14 days	High	14,15,46
vicuna		natural			Moderate	46
Class Mammalia, Order Artiodactyla, Family Cervidae						
deer, fallow	housed w/ infected steers; shows clinical signs	natural	yes		High	88
deer, mule	1924 California outbreak; shows clinical signs	natural	yes		High	25,48
deer, muntjac	housed w/ infected steers; shows clinical signs	natural	yes		High	88
deer, red	housed w/ infected steers; no clinical signs	natural	yes		High	88
deer, roe	housed w/ infected steers; shows clinical signs	natural	yes		High	88
deer, sika	housed w/ infected steers; shows clinical signs	natural	yes		High	88
deer, spotted	shows clinical signs	natural			Moderate	80
deer, white-tailed	shows clinical signs	natural	yes	11 weeks	High	89
elk	wild elk had FMD lesions; shows clinical signs	natural			Moderate	90
moose		natural			Moderate	46
reindeer	shows clinical signs?	natural			Moderate	46
sambar	shows clinical signs	natural			Moderate	80
Class Mammalia, Order Artiodactyla, Family Suidae						
babirusa		natural			Moderate	91
bush pig	shows clinical signs	natural			Moderate	11,13,91
hog, giant forest		natural			Moderate	91
pig, domestic	shows clinical signs; emits up to 3,000 times more virus in aerosol than ruminants	natural	yes	none	High	13,18,38,45, 54,92,93
pig, feral	wild boar; no reports on level of virus excretion	natural			Moderate	46,91
wart hog	shows clinical signs; virus excretion low compared to domestic pigs	natural			Moderate	11,12,79,91

Table 12 (cont.). Foot-and-Mouth Disease Virus in Live Animals

Animal	Comments	Natural or experimental host[1]	Transmission demonstrated?	Length of carrier status[2]	Hazard category	Reference
Class Mammalia, Order Artiodactyla, Other						
giraffe	shows clinical signs	natural			Moderate	11,46,47
peccary	mildly affected	natural			Moderate	46,47,91
Class Mammalia, Order Carnivora						
bear, grizzly		experimental			Low	13
cat	low susceptibility	natural			Moderate	46
dog	low susceptibility	natural			Moderate	11,46
fox	mechanical vector?	natural	yes		High	11
Class Mammalia, Order Primates						
human	shows clinical signs; may carry virus up to 14 days if clinically affected	natural	yes	36 hrs. (nasal passages)	High	13,16,17,47, 62,94
monkey	Cebidae; no clinical signs	experimental	no		Low	95
Class Mammalia, Order Proboscidea						
elephant, African		experimental	no		Low	79
elephant, Asian	shows clinical signs	natural	no		Low	11,47,96
Class Mammalia, Order Rodentia						
capybara	shows clinical signs	natural	yes	7 to 17 days	High	97
chinchilla		experimental			Low	13
coypu (nutria)	mechanical vector?	natural	yes		High	11,46
guinea pig		experimental		94 days	Low	46,47
hamster		experimental			Low	46
hamster, Syrian	low susceptibility	natural			Moderate	11
mouse	low susceptibility; certain strains are natural hosts, others experimental only	see comment			Moderate	13,46,47
muskrat		experimental			Low	13
porcupine		natural			Moderate	46
rat	low susceptibility; shows clinical signs; significance may be as mechanical vector	natural	yes		High	11,46
squirrel, gray	low susceptibility	natural			Moderate	11
squirrel, Indian	shows clinical signs	experimental	no		Low	98
vole	low susceptibility	natural			Moderate	11

Table 12 (cont.). Foot-and-Mouth Disease Virus in Live Animals

Animal	Comments	Natural or experimental host[1]	Transmission demonstrated?	Length of carrier status[2]	Hazard category	Reference
Class Mammalia, Superorder Marsupialia						
bandicoot		experimental			Low	13
kangaroo, gray	shows clinical signs	natural	yes		High	11,46
kangaroo, red	shows clinical signs	natural	yes		High	11,46
kangaroo, tree	shows clinical signs	natural	yes		High	11,46
opossum		natural			Moderate	46
potoroo		experimental			Low	13
wallaby		natural			Moderate	46
wombat		natural			Moderate	46
Class Mammalia, Other						
armadillo		experimental			Low	13
bat, vampire	shows clinical signs	experimental	no		Low	99
echidna		natural			Moderate	46
hedgehog	usually mechanical vector?; shows clinical signs	natural	yes		High	11,46,100
rabbit		experimental			Low	11,46,47
tapir		natural			Moderate	11
Vertebrates, Other						
chicken		experimental			Low	56
frog	no clinical signs	experimental	no		Low	1,13
snake	no clinical signs	experimental	no		Low	1,13
starling	mechanical vector; no clinical signs	natural	yes	droppings: 26 hrs. externally: 91 hrs.	High	11,101,102, 103
turtle	no clinical signs	experimental	no		Low	1,13
Invertebrates						
earthworm	kept in infected soil, inoculated into cattle; no clinical signs	natural	yes[3]		Moderate	11,46
fly, house	mechanical vector?; no clinical signs	natural		10 weeks	High	11,18,76
fly, biting	no clinical signs	natural	yes		High	46
tick	no clinical signs	natural	yes[3]	15-20 weeks	High	11,18

1 natural hosts are animals that have acquired FMD in a natural setting or that have been experimentally infected in a way that could occur naturally; experimental hosts are animals that have only been infected in a way that is unlikely to occur naturally

2 maximum reported length of carrier status or viral shedding

3 transmission was shown only under experimental conditions that would be unlikely to occur naturally; ability to transmit FMDV was thus considered to be "unknown"

Table 13. Foot-and-Mouth Disease Virus in Animal-Origin Products and Byproducts

Product or byproduct	Comments	Processing or storage conditions	Virus survival[1]	Transmission demonstrated?	Hazard category	Reference
Nonfood Products or Byproducts						
biologics (vaccine)	Live virus in FMD vaccines found to cause outbreaks; other vaccines unlikely to be FMD-contaminated given current QA techniques			yes	High*	1,13,14,25
embryos, bovine	virus found only in zona pellucida-free embryos exposed in vitro	in vivo transfer of zona pellucida-intact, washed embryos	no	no	Low	20,21,22, 23,104
hides or skins		green-salted, 15°C	90 days	yes	High	11,25
		green-salted, 4°C	352 days		High	
		salt & chlorine, 15°C	4 weeks		High	
		air dried, 20°C	6 weeks		High	
		salt & air	4 weeks		High	
manure, bovine	variable presence reported in feces	summer	1 week		Moderate	18,105
		winter	24 weeks		High	
		liquid @ 12-22°C	6 weeks		High	11,13,106, 107
		liquid (frozen) @ ≤0°C	180 days		High	
pituitary extract, bovine		1-7°C	>30 days	yes	High	13,18
semen, bovine	FMDV found in semen collected 42 days after contact exposure	frozen @ -50°C	320 days	yes	High	1,11,13,18, 108
semen, porcine				no	Low	24
wool, sheep		ambient temperature	20 days		High	11,18
Food Products						
bacon		salt-cured, 1-7°C	10 days		Moderate	18,30
		salted	183 days		High	
beef	ground	63°C in nylon tubes	yes		Moderate**	109,110
		79.4°C in nylon tubes	no		Low	
	whole	fresh / chilled (4°C)	3 days	yes	Moderate	11,18,46, 111
		frozen (-20°C)	3 months		High	
		quick frozen; no maturation period	8 months		High	

Table 13 (cont.). Foot-and-Mouth Disease Virus in Animal-Origin Products and Byproducts

Product or byproduct	Comments	Processing or storage conditions	Virus survival[1]	Transmission demonstrated?	Hazard category	Reference
blood, bovine		salt-cured meat	50 days		High	56,112
		clotted; stored @ 4°C	4 months		High	
		55°C for 15 min.	yes		Moderate**	
		60°C for 2 min.	no		Low	
bone marrow, bovine		refrigerated carcass	73 days		High	18,56
		1-4°C	30 weeks		High	
bone marrow, porcine	from hams or shoulders		169 days		High	30
		1-7°C	6 weeks		High	18
butter, cultured	virus survives processing	93°C for 15 sec., fermentation, stored @ 4°C	4 months		High	109,113, 114
buttermilk			14 days		High	18
casein, dried, bovine	virus survives processing	stored @ 25°C	6 weeks	yes[2]	High	113,115, 116,117
			2 months		High	
cheese, Camembert	minimum curing time is 21 days	heat + 21 days curing	< 14 days after curing		Moderate	35,109
cheese, cheddar (from raw milk)	virus survives minimum curing time	60 days curing (minimum curing time)	yes		Moderate**	35
		120 days curing	no		Low	
cheese, cheddar (bacterial ripened)		heat + processing	yes		Moderate**	35,109
		heat + processing + 30 days curing	no		Low	
cheese, Edam			22 hours		Moderate	18
cheese, mozzarella		heat + processing	no		Low	35,109
cream		93°C for 15 sec.	yes		Moderate**	109,118
ham			16 weeks		High	30
ham, Iberian	virus inactivated by curing	commercial curing (365-730 days)	< 168 days of curing		Low	32
ham, Parma	virus inactivated by curing	commercial curing (≥365 days)	< 170 days of curing		Low	34
ham, Serrano	virus inactivated by curing	commercial curing (180-365 days)	< 182 days of curing		Low	32
intestinal casings, sheep		cleaned, salted, stored @ 4°C	14 days		High	119
intestinal casings, swine			250 days		High	29,112,113
		24 hrs in brine @ 4°C	26 days		High	
		0.5% citric or lactic acid for 5 min.	no		Low	

Table 13 (cont.). Foot-and-Mouth Disease Virus in Animal-Origin Products and Byproducts

Product or byproduct	Comments	Processing or storage conditions	Virus survival[1]	Transmission demonstrated?	Hazard category	Reference
lymph node, bovine		salt-cured meat	50 days		High	18,56,120
		1-4°C	120 days		High	
		salts & citric acid cure, chilled, frozen	no		Low	
		heated to 155°F in canned ground beef	no		Low	
lymph node, porcine		1-7°C	10 weeks		High	18
meatballs	included soy protein, salt, other seasonings	93.3°C in nylon tubes	no		Low	109,110
milk, bovine	whole or skim milk; see Figure 3 for thermal death curve of FMDV in milk	72°C for 300 sec.	yes	yes	Moderate**	18,37,108, 109,113, 117,118, 121,122, 123,124, 125,126, 127
		110°C for 30 sec.	yes		Moderate**	
		110°C for 180 sec.	no		Low	
		120°C for 30 sec.	no		Low	
		138°C for 2.5 sec.	yes		Moderate**	
		148°C for 3 sec.	no		Low	
		stored @ 4°C	6 days		Moderate**	
		dried	2 years		High	
pork	muscle tissue	1-7°C	<1 day		Moderate	18,27
		frozen	>55 days		High	
rumen, bovine (tripe)		stored @ 4°C	4.75 months		High	111
salami, Italian	pork	usual process: mincing, drying, casing	no		Low	28,112
sausage, dry			<56 days		High	30
sausages	pork?	salt-cured, 1-7°C	4 days	yes	Moderate	18,49
soups / broths	derived from animal tissue	70°C for 25 min.	no		Low	112
tongue, bovine		frozen @ -50°C	11 years		High	18
venison, Impala		muscle stored @ 4°C	3 days		Moderate	128
		lymphoid stored @ 4°C	6 days		Moderate	
whey, acid		72°C for 15 sec.; pH 4.6	no		Low	109,129
whey, sweet		72°C for 15 sec.; pH 5.2	yes	no	Low	109

1 longest reported virus survival under conditions specified
2 experimental transmission only
* given direct use in animals
** long survival or direct use in animals would move to "High" hazard category

Figure 1

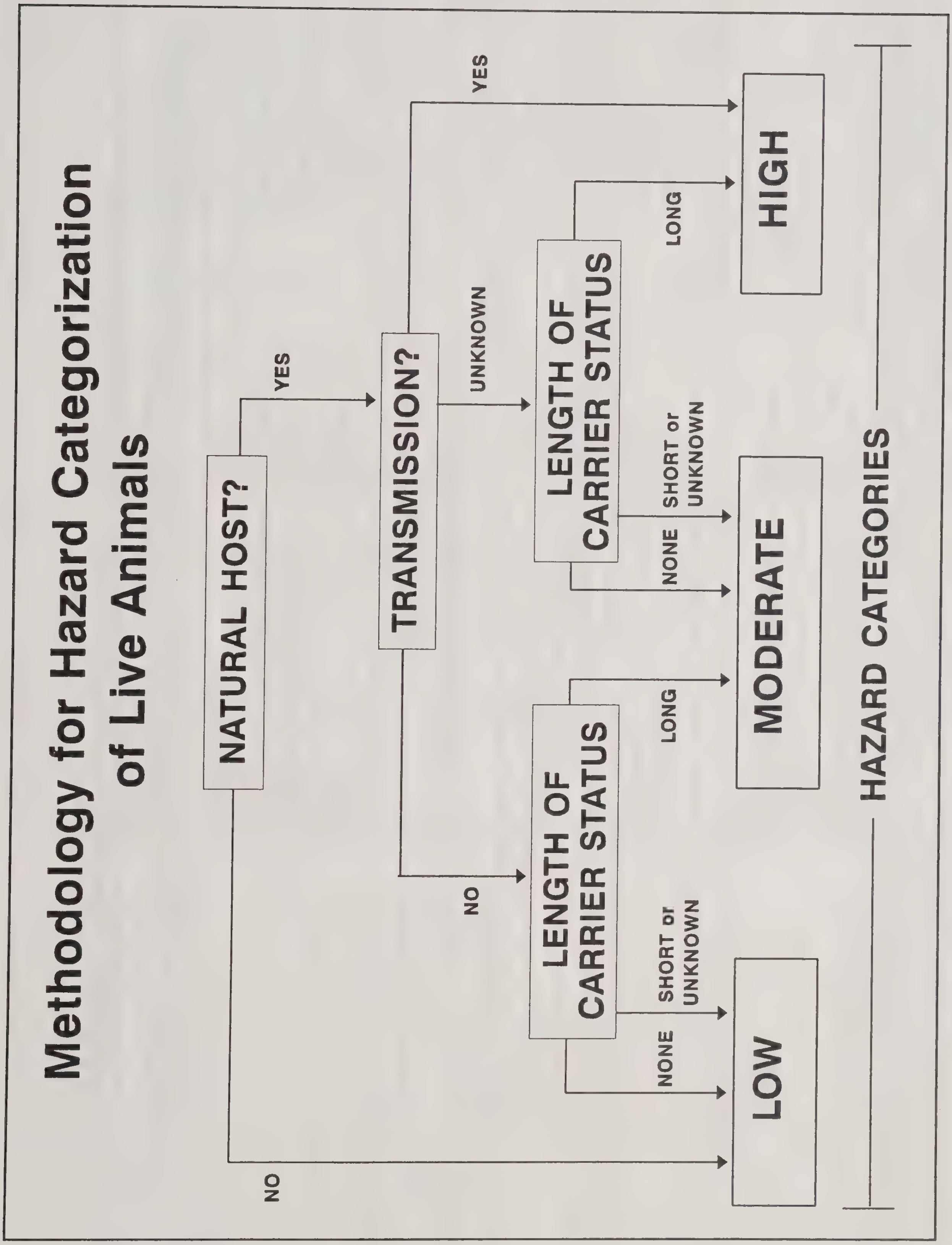

Methodology for Hazard Categorization
of Live Animals
NATURAL HOST?
YES
NO
TRANSMISSION?
YES
UNKNOWN
NO
LENGTH OF
CARRIER STATUS
LONG
SHORT or
UNKNOWN
NONE
LENGTH OF
CARRIER STATUS
LONG
SHORT or
UNKNOWN
NONE
HIGH
MODERATE
LOW
HAZARD CATEGORIES

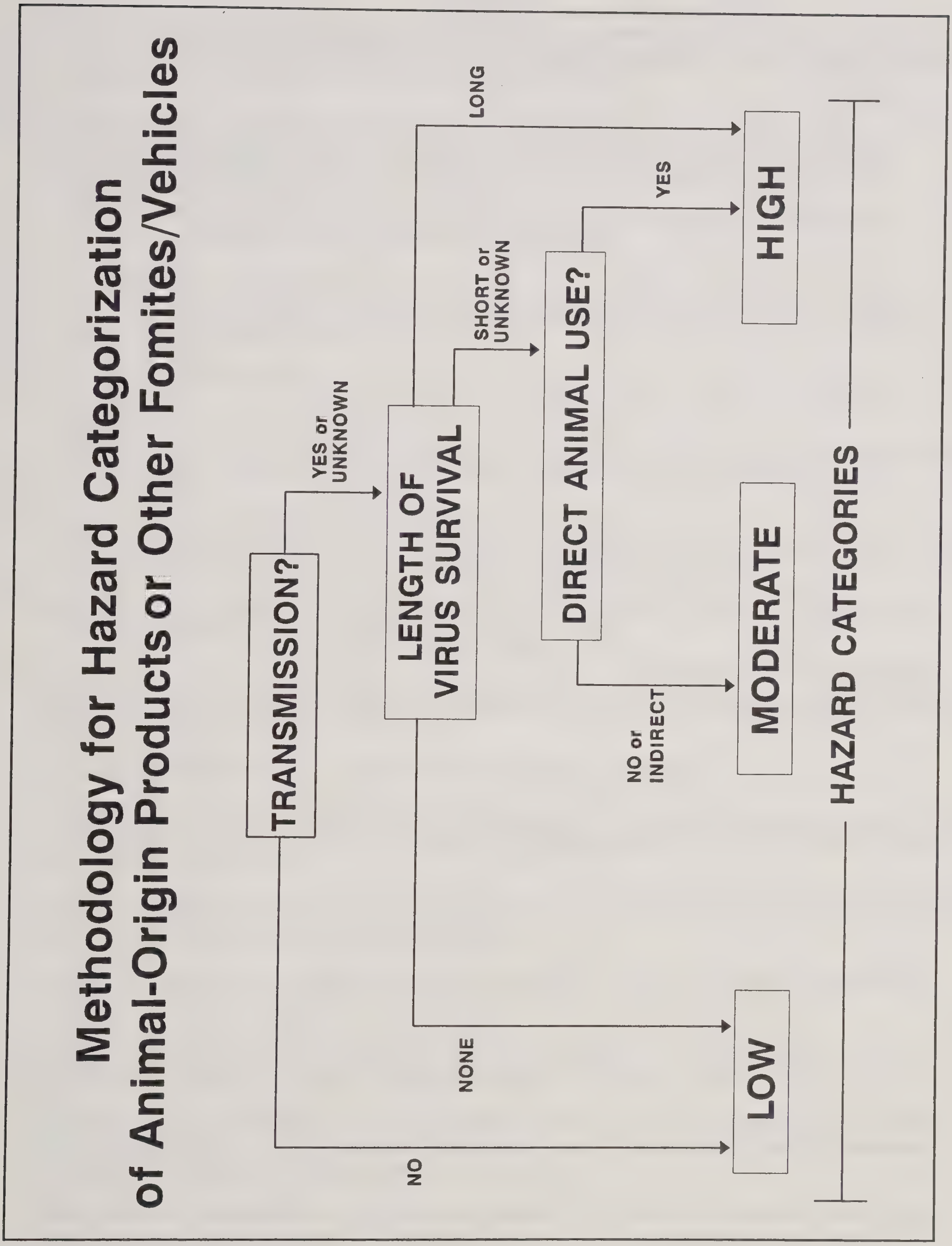
Table 14. Foot-and-Mouth Disease Virus on or in Other Fomites or Vehicles

Fomite or vehicle	Comments	Conditions	Virus survival (time or distance)[1]	Transmission demonstrated?	Hazard category	Reference
air (wind)	virus survival highly dependent on relative humidity of ≥60%	experiment during fall & winter; relative humidity ≥60%	≥60 min	yes	Moderate	37,38,41,42, 43,44,45,57, 130,131
		over land	60 km			
		over sea	250 km			
		virus sprayed into air-tight dark room	24 hours			
bedding	straw, wood-shavings		4 weeks	yes	High	105,132
clothing			100 days	yes	High	18,132
		summer	9 weeks		High	
		winter	14 weeks		High	
equipment / utensils	buckets, tools			yes	Moderate	11
feed / fodder	bran		20 weeks	yes	High	11,61,62,105, 132
	hay	ambient temperature	>200 days		High	
	wheat				High*	
garbage	contained animal products or byproducts			yes	High*	25,64
packing / wrapping materials		room temperature	46 days	yes	High	11,46,62
seeds				yes	Moderate	61
shoes or boots		summer	9 weeks		High	18,132
		winter	14 weeks		High	
soil		summer	3-7 days		Moderate	18,93,106
		autumn	4 weeks		High	
		winter	21 weeks		High	
vegetables		ambient temperature	7 days	yes	High	18,61,105
vehicles	trucks, bicycles, "carriages"			yes	Moderate	1,62,133,134
water		ambient temperature	14 weeks		High	11,18,46
		summer / autumn	15 days		High	

1 longest reported time or distance of virus survival under conditions specified

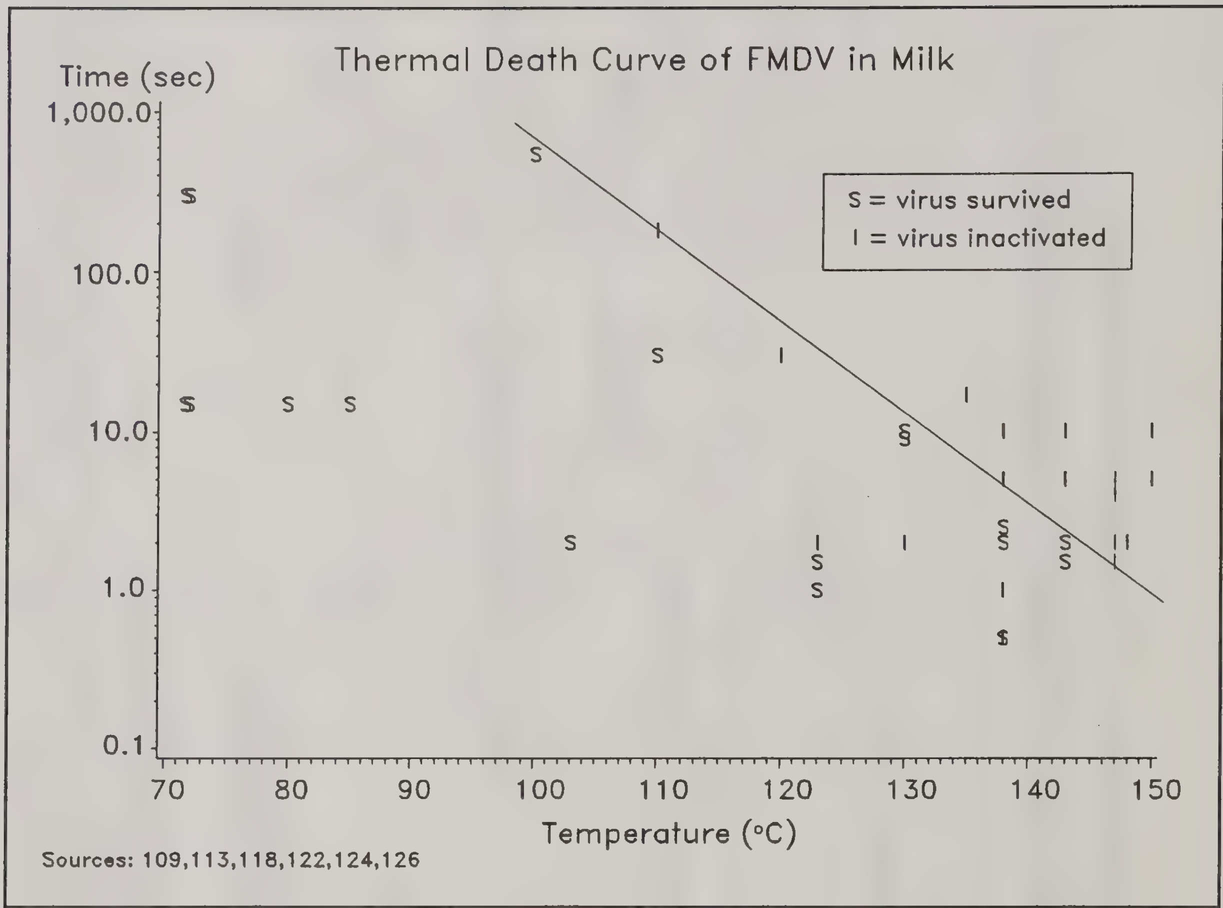
* given direct use in animals

Figure 2



Methodology for Hazard Categorization of Animal-Origin Products or Other Fomites/Vehicles
TRANSMISSION?
NO
YES or UNKNOWN
LENGTH OF VIRUS SURVIVAL
NONE
SHORT or UNKNOWN
LONG
DIRECT ANIMAL USE?
NO or INDIRECT
YES
LOW
MODERATE
HIGH
HAZARD CATEGORIES

Figure 3


Thermal Death Curve of FMDV in Milk
Time (sec)
1,000.0
100.0
10.0
1.0
0.1
S = virus survived
I = virus inactivated
70
80
90
100
110
120
130
140
150
Temperature (°C)
Sources: 109,113,118,122,124,126

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